

POMERON: BEYOND THE STANDARD APPROACH ^a

K. GOULIANOS

*The Rockefeller University, 1230 York Avenue, New York,
NY 10021, USA*

E-mail: dino@physics.rockefeller.edu

We discuss the experimental evidence supporting the concept of universality of the rapidity gap probability in soft and hard diffraction, relate the gap probability to hadronic parton densities, and present a phenomenological model of diffraction in which the structure of the Pomeron is derived from the structure of the parent hadron. Predictions for diffractive deep inelastic scattering are compared with data.

1 Introduction

Experiments at HERA and at hadron colliders have reported and characterized a class of events incorporating a hard (high transverse momentum) partonic scattering while carrying the characteristic signature of diffraction, namely a leading (anti)proton and/or a large *rapidity gap* (region of pseudorapidity devoid of particles). The prevailing theoretical idea is that the exchange across the gap is the Pomeron¹, which in QCD is a color-singlet exchange of gluons and/or quarks with vacuum quantum numbers.

A question of intense theoretical debate is whether the Pomeron has a unique particle-like partonic structure. This question can be addressed experimentally by comparing the parton distribution functions (*pdf*'s) of the (anti)proton measured in a variety of hard single diffraction dissociation processes as a function of ξ , t , Q^2 and x (or $\beta \equiv x/\xi$), where t is the 4-momentum transfer and ξ the fractional momentum loss of the (anti)proton. The gluon and quark *pdf*'s can be sorted out by studying processes with different sensitivity to the gluon and quark components of the Pomeron.

The proton diffractive *pdf*'s have been measured in diffractive deep inelastic scattering (DDIS) at HERA by both the H1² and ZEUS³ Collaborations. The experiments measure directly the F_2 diffractive structure function, $F_2^{D(3)}(\xi, Q^2, \beta) = \int_{t=-1}^{t_{min}} F_2^{D(4)}(t, \xi, Q^2, \beta) dt$. The variable ξ is related to the rapidity gap by $\Delta y = \ln \frac{1}{\xi}$. The gluon diffractive *pdf* was determined by H1 from a QCD analysis of the Q^2 evolution of $F_2^{D(3)}$. All HERA hard diffraction results are generally consistent with the parton densities obtained from DDIS.

^aTo appear in Proceedings of "XXIX International Symposium on Multiparticle Dynamics, 9-13 August 1999, Brown University, Providence, RI 02912, USA".

However, assuming factorization, calculations based on these *pdf*'s predict^{4,5,6} rates ~ 10 times larger than the measured W and dijet production rates at the Tevatron⁷. The suppression of Tevatron relative to HERA diffractive rates represents a breakdown of factorization.

The magnitude of the factorization breakdown is in general agreement with predictions based on the renormalized Pomeron flux model⁸, in which the Pomeron flux (see next section) is viewed⁹ as a rapidity gap probability density and is normalized by scaling it to its integral over the available phase space in (ξ, t) . In addition to its success in predicting soft and hard diffraction rates, the flux renormalization model describes *differential* soft diffraction cross sections¹⁰ remarkably well. However, the β -dependence of the Pomeron/diffractive *pdf*'s is not specified by the model and had to be introduced “by hand”. In this paper, the diffractive *pdf*'s are derived from the non-diffractive using a parton model approach to hard diffraction based on the the concept of a normalized rapidity gap probability.

2 Clues from soft physics

The Pomeron was introduced in Regge theory to account for the high energy behavior of the elastic, diffractive and total hadronic cross sections. In terms of the Pomeron trajectory, $\alpha(t) = 1 + \epsilon + \alpha' t$, the pp cross sections can be written as

$$\sigma_T(s) = \beta_{\mathbb{P}pp}^2(0) \left(\frac{s}{s_0} \right)^{\alpha(0)-1} \sim \left(\frac{s}{s_0} \right)^\epsilon \quad (1)$$

$$\frac{d\sigma_{el}}{dt} = \frac{\beta_{\mathbb{P}pp}^4(t)}{16\pi} \left(\frac{s}{s_0} \right)^{2[\alpha(t)-1]} \sim \exp[(b_0 + 2\alpha' \ln s)t] \quad (2)$$

$$\frac{d^2\sigma_{sdd}}{d\xi dt} = \underbrace{\frac{\beta_{\mathbb{P}pp}^2(t)}{16\pi} \frac{1}{\xi^{2\alpha(t)-1}}}_{\text{Pomeron flux} \sim \frac{1}{\xi^{1+2\epsilon}}} \underbrace{\beta_{\mathbb{P}pp}(0) g(t) \left(\frac{\xi s}{s_0} \right)^{\alpha(0)-1}}_{\sigma_T^{\mathbb{P}p} \sim (\xi s)^\epsilon} \quad (3)$$

The Regge approach has been successful in predicting the three salient features of high energy behavior, namely (i) the rise of the total cross sections with energy^{11,12}, (ii) the shrinking of the forward elastic scattering peak¹³, and (iii) the shape of the M^2 dependence of SDD^{10,13}. However, these features are also present in a parton model approach¹⁴, as outlined below.

2.1 Rise of total cross sections

The pp total cross section is basically proportional to the number of partons in the proton, integrated down to $x = s_o/s$, where s_o is the energy scale for soft physics. The latter is of $\mathcal{O}(\langle M_T \rangle^2)$, where $\langle M_T \rangle \sim 1$ GeV is the average transverse mass of the particles in the final state. Expressing the parton density as a power law in $1/x$, which is an appropriate parameterization for the small x region responsible for the cross section rise at high energies, we obtain

$$\sigma_T \sim \int_{(s_o/s)}^1 \frac{dx}{x^{1+n}} \sim \left(\frac{s}{s_o} \right)^n \quad (4)$$

The parameter n is identified with the $\epsilon = \alpha(0) - 1$ of the Pomeron trajectory.

2.2 Shrinking of forward elastic peak

In Regge theory, the slope of the forward elastic peak increases as $\ln s$, while in the parton picture one would naively expect the slope to follow the increase of the total cross section:

$$\frac{d\sigma^{el}}{dt} \sim \underbrace{\exp[(b_o + 2\alpha' \ln s)t]}_{\text{Regge}} \Rightarrow \sim \underbrace{\exp[(b_o + cs^n)t]}_{\text{Parton model}} \quad (5)$$

Using $n = \epsilon = 0.104$ ¹⁰, we note that from $\sqrt{s} = 20$ to 1800 GeV the terms $\ln s$ and s^n increase by factors of 2.50 and 2.55, respectively. Thus, the Regge and parton model expressions for the slope are experimentally indistinguishable.

2.3 M^2 dependence of diffraction dissociation

The diffractive mass is related to ξ by $M^2 \approx \xi s$. In the Regge picture, the $t = 0$ single diffractive cross section^b is given by (see Eq. 3)

$$\text{Regge : } \frac{d\sigma_{sdd}}{dM^2} \sim \frac{s^{2\epsilon}}{(M^2)^{1+\epsilon}} \quad (6)$$

However, experimentally the cross section is found to be independent of s ^{8,10}:

$$\text{Experiment : } \frac{d\sigma_{sdd}}{dM^2} \sim \frac{1}{(M^2)^{1+\epsilon}} \quad (7)$$

^bIn the rest of this paper we use $t = 0$ cross sections for simplicity, but the results we obtain generally apply also to the cross sections integrated over t .

In terms of $\xi = \frac{M^2}{s}$, we have $\frac{d\sigma_{sdd}^{\text{exp}}}{d\xi} \sim \frac{1}{s^\epsilon} \frac{1}{\xi^{1+\epsilon}}$, which can be written as

$$\frac{d\sigma_{sdd}}{d\xi} \sim \underbrace{\frac{1}{s^{2\epsilon}} \frac{1}{\xi^{1+2\epsilon}}}_{\text{constant}} \times (\xi s)^\epsilon \quad (8)$$

Recalling that ξ is related to the rapidity gap and $\xi s = M^2$ is the s-value of the diffractive sub-system, and noting that $\int_{(s_0/s)}^1 \frac{1}{s^{2\epsilon}} \frac{d\xi}{\xi^{1+2\epsilon}} = \text{constant}$, Eq. 8 may be viewed as representing the product of the total cross section at the sub-system energy multiplied by a *normalized* rapidity gap probability. This *experimentally established* scaling behavior is used in the next section as a clue in deriving the diffractive F_2 structure function from the non-diffractive in the parton model approach to diffraction.

3 Diffractive deep inelastic scattering

The inclusive and diffractive DIS cross sections are proportional to the corresponding F_2 structure functions of the proton,

$$\frac{d^2\sigma}{dxdQ^2} \sim \frac{F_2^h(x, Q^2)}{x}; \quad \frac{d^3\sigma}{d\xi dxdQ^2} \sim \frac{F_2^{D(3)}(\xi, x, Q^2)}{x} \quad (9)$$

where the superscripts h and $D(3)$ indicate a *hard* inclusive structure (at the scale Q^2) and a 3-variable diffractive structure (integrated over t). The latter depends not only on the hard scale Q^2 , but also on the *soft* scale $\langle M_T \rangle^2$, which is the relevant one for the formation of the gap.

The only marker of the rapidity gap is the variable ξ . We therefore postulate that the rapidity gap probability is proportional to the *soft* parton density at ξ and write the DDIS cross section as

$$\frac{d^3\sigma}{d\xi dxdQ^2} \sim \frac{F_2^h(x, Q^2)}{x} \times \frac{F_2^s(\xi)}{\xi} \otimes \xi - \text{norm} \quad (10)$$

where the symbolic notation “ $\otimes \xi - \text{norm}$ ” is used to indicate that the ξ probability is normalized. Since $x = \beta\xi$, the normalization over all available ξ values involves not only F_2^s but also F_2^h , breaking down factorization. It is therefore prudent to write the DDIS cross section in terms of β instead of x , so that the dependence of F_2^h on ξ is shown explicitly:

$$\frac{d^3\sigma}{d\xi d\beta dQ^2} \sim \frac{F_2^h(\beta\xi, Q^2)}{\beta} \times \frac{F_2^s(\xi)}{\xi} \otimes \xi - \text{norm} \quad (11)$$

The term to the right of the \sim sign represents the $F_2^{D(3)}(\xi, \beta, Q^2)$ structure function. Guided by the scaling behaviour of Eq. 8, we now factorize $F_2^{D(3)}(\xi, \beta, Q^2)$ into $F_2^h(\beta, Q^2)$, the sub-energy cross section, times a normalized gap probability:

$$F_2^{D(3)}(\xi, \beta, Q^2) = P_{gap}(\xi, \beta, Q^2) \times F_2^h(\beta, Q^2) \quad (12)$$

The gap probability is given by

$$P_{gap}(\xi, \beta, Q^2) = \frac{F_2^h(\beta\xi, Q^2)}{\beta} \times \frac{F_2^s(\xi)}{\xi} \times N(s, \beta, Q^2) \quad (13)$$

where $N(s, \beta, Q^2)$ is the normalization factor,

$$N(s, \beta, Q^2) = f_q / \int_{\xi_{min}=Q^2/\beta s}^1 \frac{F_2^h(\beta\xi, Q^2)}{\beta} \times \frac{F_2^s(\xi)}{\xi} d\xi \quad (14)$$

in which f_q denotes the quark fraction of the hard structure (since only quarks participate in DIS).

3.1 Comparison with data

At small x and small ξ , the structure functions F_2^h and F_2^s are represented well by $F_2^h(x, Q^2) = A^h/x^{\epsilon^h(Q^2)}$ and $F_2^s(\xi) = A^s/\xi^{\epsilon^s}$. An analytic evaluation of Eqs. 14 and 12 yields

$$N(s, \beta, Q^2) = f_q / \left[\frac{A^h}{\beta^{1+\epsilon^h}} \frac{A^s}{\epsilon^h + \epsilon^s} \left(\frac{\beta s}{Q^2} \right)^{\epsilon^h + \epsilon^s} \right] \quad (15)$$

$$F_2^{D(3)}(\xi, \beta, Q^2) = \frac{1}{\xi^{1+\epsilon^h+\epsilon^s}} \times f_q(\epsilon^h + \epsilon^s) \left(\frac{Q^2}{\beta s} \right)^{\epsilon^h + \epsilon^s} \times \frac{A^h}{\beta^{\epsilon^h}} \quad (16)$$

Figure 1 shows a comparison of the β distribution of H1 data ² at $\xi \approx 0.01$ and $Q^2 = 45 \text{ GeV}^2$ with the prediction of Eq. 16. The following parameters were used in the calculation: $\sqrt{s} = 280 \text{ GeV}$, $\epsilon^s = 0.1$ ¹², $Q^2 = 45 \text{ GeV}^2$, $\epsilon^h(Q^2 = 45) = 0.3$, $f_q = 0.4$, $\xi = 0.01$ and $A^h = 0.2$, evaluated from $F_2(Q^2 = 50, x = 0.00133) = 1.46 \Rightarrow \frac{A^h}{x^{0.3}}$. The agreement between theory and experiment may be considered excellent, particularly since no free parameters were used in the calculation.

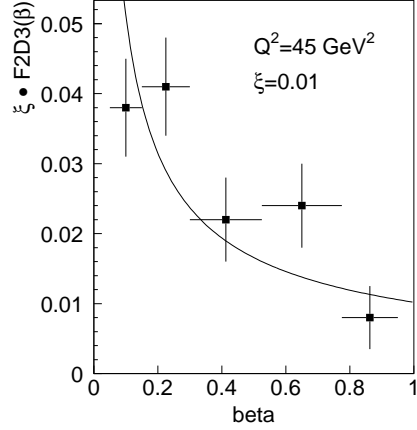


Figure 1

References

1. See, for example, P.D.B. Collins, *An Introduction to Regge Theory and High Energy Physics*, Cambridge University Press, Cambridge (1977).
2. T. Ahmed *et al.*, Phys. Lett. **B 348**, 681 (1995); C. Adloff *et al.*, Z. Phys. **C 76**, 613 (1997).
3. M. Derrick *et al.*, Z. Phys. **C 68**, 569 (1995); Phys. Lett. **B 356**, 129 (1995); Eur. Phys. J. **C 6**, 43 (1999).
4. K. Goulianos, in *Proceedings of "Vth International Workshop on Deep Inelastic Scattering and QCD,"* Chicago, USA, 1997, edited by J. Repond and D. Krakauer (AIP Conf. Proc. **407**, 1997) pp. 527-532.
5. L. Alvero, J. C. Collins, J. Terron and J. Whitmore, Phys. Rev. D **59**, 074022 (1999).
6. R.J.M. Covolan and M.S. Soares, hep-ph/9905352.
7. F. Abe *et al.*, Phys. Rev. Lett. **78**, 2698 (1997); *ib.* **79**, 2636 (1997).
8. K. Goulianos, Phys. Lett. **B358**, 379 (1995); **B363**, 268 (1995).
9. K. Goulianos, *Rapidity Gaps in Soft and Hard Diffraction*, LISHEP-98, Rio de Janeiro, Brazil, 10-20 February 1998 [hep=ph/9806384].
10. K. Goulianos and J. Montanha, Phys. Rev. **D 59**, 114017 (1999).
11. A. Donnachie and P. Landshoff, Phys. Lett. **B 296**, 22 (1992).
12. R.J.M. Covolan, J. Montanha and K. Goulianos, Phys. Lett. **B 389**, 176 (1996).
13. K. Goulianos, Physics Reports **101**, 169 (1983).
14. E. Levin, *An Introduction to Pomerons*, Preprint DESY 98-120.